Next Steps in Mars Polar Science:
In Situ Subsurface Exploration of the North Polar Layered Deposits

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Abstract:

Answering the most urgent questions in polar science will require the in situ application of terrestrial paleoclimate assessment techniques, including measurement of the ratios D/H and $^{18}O/^{16}O$ in ice or meltwater. Whether implemented with a single deep ice borehole or a series of shallow holes along a traverse, such a mission requires ***subsurface access to the polar layer deposits*** *at sufficient depth to eliminate the possibility of recent surface alteration.*

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Preamble

The study of Mars is largely occupied with understanding its history and evolution. Two pertinent time scales are the 10^8-10^9 year arc of martian history demarcated by the Noachian, Hesperian, and Amazonian epochs; and the secular changes in climate on 10^5-10^7 year time scales that are driven by Milankovich cycles and stochastic processes. The former are best studied in equatorial regions where periglacial processes have not obliterated the record. The latter, the subject of this White Paper, are best studied in the polar regions where the record is preserved in strata of ice and dust.

Visible stratigraphy within the Polar Layered Deposits (PLD) suggests a historical imprint, much like the ice record of Earth's climate (Fig. 1). Climate modulations reflected in these strata are not just relevant to modern history, but should be seen as a typical response to astronomical forcing that has been present in every epoch. Such cycles may be responsible for older sedimentary strata observed elsewhere on the planet (Lewis 2008), the deposition of low latitude surface ice and mountain glaciers (Head 2003), or the triggering of episodic events such as flooding in the Noachian and early Hesperian. Moreover, implicit in the paleoclimate record is the history of conditions for life – indicated, perhaps, by a record of amino acids, methane, or signs of past melting.

The 2003 Decadal Survey designated the North Polar Layered Deposits (NPLD) as a prime exploration target, in response to questions including "What are the sources, sinks, and reservoirs of volatiles on Mars?" and "How does the atmosphere evolve over long time periods?". Objective 6 of the 2006 SSE roadmap is a call to "Characterize the present climate of Mars and determine how it has evolved," and Objective 2 calls for a study of "Planetary processes such as… climate change."

While orbital and Earth-based campaigns will continue to contribute to our understanding of polar processes, our lack of direct, *in situ* measurements from the PLD is a conspicuous deficiency. Imagine attempting to understand the evolving climate and hydrosphere of Earth from orbital imagery alone, without direct exploration of our great ice sheets. **Accordingly, we identify a landed mission on the PLD as the next enabling step in Mars polar science.**

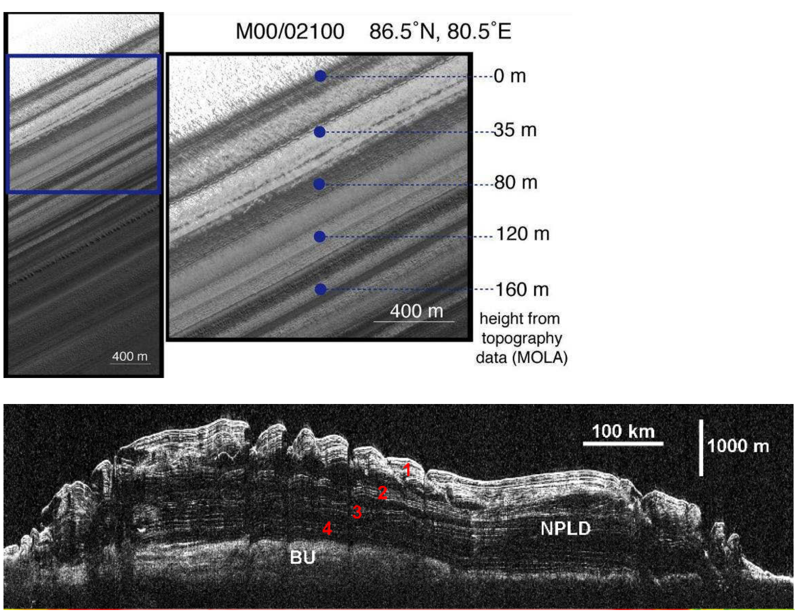

Figure 1: Top: A typical exposed section of NPLD topography indicating elevations (from MOLA). A study of 150 m of this column can be expected to transect diverse strata. A 50 m descent, while valuable, transects only a few strata and is not necessarily representative. Bottom: A SHARAD profile (courtesy NASA/JPL/Caltech) of the major stratigraphy of the NPLD, indicating the lateral conformity (Phillips 2008).

1. Major questions and investigations in Mars polar science

The past decade has witnessed significant progress in our understanding of Mars polar processes. The continuity of strata across the PLD has been confirmed with MOC images (Milkovich and Head, 2005; Fishbaugh and Hvidberg, 2006) and the MARSIS and SHARAD radar instruments (Phillips 2008). Earth-based spectroscopy has revealed large spatial and temporal variations in D/H ratios, confirming its value as a climate marker in ice (Mumma 2003). Related observations have suggested the transient release of methane in the atmosphere, a signal that could potentially be archived in the PLD (Mumma 2009). In 2008, the Phoenix mission landed on the northern plains to perform the first *in situ* study of martian ice in the form of near subsurface deposits. Results supported an equilibrium model of shallow ground ice deposition, and examples of both vapor diffused pore ice and largely particle-free ice were found at the site (Smith 2009). Phoenix also made the first observation of snowfall on Mars (Whiteway 2009).

Of the various summaries of key issues in Mars polar science (Clifford 2000, Clifford 2005, Titus 2008, Byrne 2009), arguably the most representative of community opinion is the set of driving questions identified at the 2006 International Mars Polar Science conference (Fishbaugh 2008). In this section, we attempt to update and refine those driving questions and the investigations they suggest.

Question 1: What is the mechanism of climate change on Mars? How has it shaped the planet, and how does it relate to climate change on Earth?

Investigation: Determine what seasonal and interannual variability, geologic history, and record of climatic change is expressed in the stratigraphy of Planum Boreum and Planum Australe.

High resolution orbital imagery and surface-penetrating radar profiles have revealed much about the character of the north and south PLD and residual caps. We now know, for example, that many strata are continuous across Planum Boreum. However, orbital studies are and will remain insufficient to link the stratigraphy to Milankovich cycles, or even to definitely prove that it does not derive from stochastic processes (Perron 2009). In situ subsurface access is needed to capture fine scale stratigraphy (e.g. annual cycles of deposition); to measure climate markers such as isotopic fractionation, dust content and entrained salts; to establish a record of global events; to seek evidence of episodes of liquid water and ice flow; and to establish an absolute chronology.

Question 2: How do the PLD evolve, and how are they affected by planetary-scale cycles of water, dust, and CO_2?

Investigation: Determine the physical characteristics of the polar layered deposits and residual caps.

Investigation: Determine the mass & energy budgets of the PLD, residual caps, and seasonal caps, and what processes control these budgets on seasonal and longer timescales.

Total mass and energy budgets, feedback processes, and the inventory of water, dust, and CO_2 in the PLD and residual caps are still poorly understood, as are the differences between the NPLD and the SPLD. We do not understand how cumulative seasonal effects combine with interannual variability, such as intermittent large dust storms, to control the mass-balances of ices and dust on the residual caps and PLD. Nor do we understand how these factors vary with changes in orbital elements. Generation of lag *deposits and the establishment of a residual CO_2 cap on either pole may exert a major influence on the evolution of the PLD. Morphological features such as the great chasma and the smaller troughs and scarps that bound the PLD in places suggest that nonuniform erosional processes are important. Nonpolar sources and sinks of volatiles presumably affect the deposition of polar layers, but the details are unclear. To further our understanding of these processes requires knowledge of the geology within, beneath, and surrounding the PLD; the composition and density of the ice; the particulate and volatile content; grain size and structure; and the physical properties of the PLD such as the mechanical strength, temperature distribution, and stress-strain characteristics. Theoretical analysis, orbital reconnaissance, and* in situ *meteorological measurements to constrain current conditions (including the radiation budget), will all contribute to an improved understanding of the evolution of the PLD.*

Question 3: What is the global history of ice on Mars? Where is it sequestered outside the polar regions, and what disequilibrium processes allow it to persist there?

Investigation: By comparing polar and non-polar ice, determine the relationship between the PLD and residual cap record and processes elsewhere on Mars.

Predicted over 40 years ago and confirmed by Odyssey's Gamma Ray Spectrometer suite, shallow deposits of ice at high latitudes constitute a significant fraction of the planetary inventory of water. Numerous studies, including the Phoenix mission, radar observations, and investigations of small meteorite impacts, have failed to reveal the formation mechanism of this ice, the extent to which volatiles are exchanged with polar sources and sinks, or even its vertical extent. Moreover, numerous suggestions of low latitude buried ice deposits in disequilibrium have appeared in recent literature. This cross-cutting question is included here because its resolution will require not only physical investigation of the character and extent of these deposits, but an understanding of climate history, energy and mass budgets that will derive from studies of the PLD.

2. Approach to subsurface access

At a minimum, a PLD subsurface investigation would be expected to:

- Explore several layers of the stratigraphy visible from orbit.
- Analyze D/H and $^{18}O/^{16}O$ (depth resolution of ~1 cm is feasible)
- Visually measure dust concentration and ice structure (depth resolution of <1 mm is feasible)
- Measure soluble chemical species (depth resolution of ~1 cm is feasible)
- Monitor seasonal polar weather

It has been established from radar observations that the PLD consist of nearly pure ice (Phillips 2008). Deep excavation of such ice can be accomplished with modest infrastructure and with high reliability. One example of a Mars-compatible drill has been provided by a JPL group (Hecht 2007; Bentley 2009), who used a small, portable thermal drill to bore through 50 meters of Greenland ice in approximately two days, returning meltwater for analysis and performing down-hole imaging (Fig. 2). Studies for Scout-class missions using this drill indicate that a 50-m descent is possible on a Phoenix-like platform in a solar-powered summer mission. With the addition of an Advanced Stirling Radioisotope Generator (ASRG) the range extends to 150-m, transecting numerous strata (Fig. 1). This long-lived station would also monitor seismic activity, weather patterns, and mass and energy balance[1]. A recent study under NASA's DSMCE program concluded that the cost of such a mission, exclusive of launch vehicle, ASRG, or full spacecraft sterilization (if required), could be as low as $400M (FY'08).

Alternatively, the required samples and observations could be acquired by rover traverse down an exposure of PLD using an ice corer or other means of subsurface sampling. Roughly 100 boreholes would be required to adequately sample the PLD along the traverse, depending on the length of the coring drill. While this approach is feasible, and there may be programmatic reasons to prefer a rover-based mission, surface mobility seems to offer little or no technical or scientific advantage over a single deep borehole. The payload size and the inevitable requirement of a radioisotope power source would likely require an MSL-class mission, as compared to a Phoenix-class mission for the stationary platform.

Figure 2: A 7 cm diameter thermal drill descends into the Greenland ice cap returning meltwater for analysis through an aerogel-insulated tether. In the final frame, the drill is 47 m below the surface (images from JPL).

3. Measurements

Terrestrial experience suggests that observable properties of ice strata can be related to the climate conditions that prevailed during their formation. The observed PLD stratigraphy suggests that exploration of tens to hundreds of meters of the column is required (Fig. 1), with centimeter-scale resolution desirable for chemical and isotopic measurements, sub-millimeter resolution for optical measurements. Assuming such access to buried strata, the following measurements are high priorities for the investigations defined above:

- **Microscopic observation** of the stratigraphy to determine whether the visual and radar modulations are due to variations in dust density, particle size and spatial distribution, aggregation, or ice grain structure; to ascertain whether the dust density is simply modulated, or whether lag deposits are present; to quantify the density profile and detect the expression of fine structure below the resolution limit of orbital imagery; and to characterize any firn layer. ***Specific inquiries:*** Does the

[1] It should be noted that, while the ASRG or other radioisotope power source is a prerequisite for year-round polar observations, the combination of a perennial heat source and polar ice poses a possible planetary protection violation in the event of an anomalous landing. Strategies to deal with this eventuality range from the inexpensive application of a biocide to the radioisotope source, to Viking-class full spacecraft sterilization.

stratigraphy reflect changes in dust accumulation rate, ice accumulation, alternating cycles of net accumulation and sublimation, or some combination of these phenomena? Can annual layers be observed, allowing absolute chronology? Can discrete events such as emplacement of impact ejecta or fallout from volcanic activity be identified? What are the seasonal and longer timescale variations in water-ice properties (e.g., grain size, compaction, accumulation and loss rates)? What hydrostatic and dynamic processes such as grain metamorphism and deformation are expressed in the variation of grain structure with depth? To what extent are atmospheric gases incorporated into the bulk ice as bubbles? ***Technology:*** The technology to perform such measurements is comparable to that of the MER Microscopic Imager or the Phoenix Robotic Arm Camera.

- **Isotopic analysis** of the ice or meltwater provides primary indicators of past climate conditions. Without the moderating influence of oceans, atmospheric D/H is known from Earth-based observations to vary over a much larger range on Mars than on Earth (Mumma 2003). This phenomenon has been attributed to sampling from different reservoirs (PLD, ground ice, etc.), and the time sequence will therefore reflect global climate conditions (Fisher 2007). Similar behavior is expected of the $^{18}O/^{16}O$ ratio. ***Specific inquiries*:** What is the connection between orbital/axial variations and layering of various scales within the PLDs? Can the internal layers be dated (relatively and absolutely), and what portion of Mars' history do these layers represent? What can the physical, chemical, and isotopic properties of the strata tell us about the depositional environment of each layer? What does the Mars climate record tell us about climate change on Earth with respect to such factors as the solar cycle, Milankovic cycles, and feedback mechanisms? ***Technology:*** Instrumentation to measure the isotopic ratios in H_2O and CO_2 to within a few parts per thousand derives from the diode laser spectrometer that flew on Mars Polar Lander and the TLS instrument on MSL (an implementation specific to melt-water has been developed under the PIDDP program).

- **Chemical analysis:** A history of major soluble or partially soluble components of particulates and salts embedded in the ice over time might include sulfates, halides, perchlorates, carbonates, associated cations, and overall dielectric properties. ***Specific inquiries:*** How is the stratigraphy of the PLD related to episodic events such as impacts, volcanic eruptions, global dust storms, and melting (evidenced by evaporitic deposits)? What record of volatiles such as methane, or photochemical products such as perchlorate, is recorded in the PLD? Is there evidence of past or present melting, and how does this relate to age? ***Technology:*** Inorganic aqueous analysis can be performed with mature electrochemical techniques such as those used in Phoenix, or with spectroscopic techniques such as Raman. Capture and analysis of dissolved gases is yet to be demonstrated.

- **Surface meteorology:** A present-day meteorological record should include diurnal, seasonal and interannual variations in the atmospheric temperature profile; pressure; wind speed and humidity profiles; dust and ice (both H_2O and CO_2) accumulation rates; atmospheric opacity; and observation of aeolian activity of dust and ice. ***Specific inquiries:*** What constraints does surface meteorology provide on radiative energy balance, present-day mass balance (accumulation/ablation) of the ice and dust, and the supply of atmospheric water vapor and dust to the polar regions? Can observations of aeolian activity be related to observed resurfacing rates (Herkenhoff 2000)? To present-day accumulation and sublimation rates? ***Technology:*** The Phoenix mission effectively implemented these technologies at modest cost. Measurements of meteorology spanning one or more martian years will require a radioisotope power source.

4. Opportunistic Science enabled by a PLD mission

We also identify two investigations that, while not directly relevant to polar processes, are of great importance to the study of Mars and are conveniently implemented on a polar platform.

Investigation: Extract a chronological record of biomarkers from the PLD.

Aqueous detection methods such as capillary electrophoresis may allow recovery of trace levels of amines, polycyclics, and nucleobases, which are indicative of prebiotic processes (a "follow the nitrogen" strategy as suggested by Capone 2006). Also of interest are oxidants, presumably of photochemical origin, and dissolved methane.

Investigation: Monitor planet-wide seismic activity and measure the geothermal constant from a polar subsurface platform.

By embedding seismometers and strain gauges in polar ice, the ice sheets become vast and sensitive detectors of seismic activity. While even a single seismic station can reveal much about the radial structure of Mars, in coordination with low latitude seismometers a polar station will allow 3-D reconstruction of the geophysical structure of the planet. In a borehole, the thermally uniform nature of polar ice should allow accurate and sensitive measurements of the geothermal flux.

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